Assessment of MODIS On-orbit Polarization Impact on Detector Relative Calibration

A. Wu[a] and X. Xiong[b]

[a]Science Systems and Applications, Inc., Lanham, MD

[b]NASA Goddard Space Flight Center, Greenbelt, MD

Abstract

The Moderate-Resolution Imaging Spectroradiometer (MODIS) has been maintained its nominal operations since it was launched in December 1999 on Terra and May 2002 on Aqua spacecraft, respectively. MODIS is a scanning radiometer with a two-sided mirror that scans the Earth over an angular range from -55° to +55° off nadir and covers a wavelength range from 0.4 to 14.4 μm in 36 spectral bands. The sensitivity to polarization was fully characterized during prelaunch characterization for each reflective solar band (RSB), detector and mirror side as a function of scan angle. It was observed that while on-orbit polarization sensitivity for Aqua MODIS has been stable over the course of mission, the Terra MODIS polarization sensitivity at a few short wavelengths showed a significant increase near the end of scan angle after a few years in the mission. Our previous study examined the impact of polarization on the measured top-of-atmosphere reflectances obtained over the pseudo-invariant desert sites. There are up to 25% change in gain and 30% seasonal variation in select Terra RSBs due to the increase in polarization sensitivity. In this study, we examine relative changes in the polarization sensitivity of detectors within a band. Results from prelaunch tests indicate that there is a noticeable detector dependent polarization sensitivity and it is expected that such a dependency could change on orbit, particularly for Terra MODIS. Results of this study provide useful information on polarization impact and implementation of the correction algorithm.

1. INTRODUCTION

MODIS has been operating nominally since it was launched in December 1999 on Terra and May 2002 on Aqua spacecraft, respectively. It is a scanning radiometer with a two-sided mirror that scans the Earth over an angular range from -55° to +55° off nadir and covers a wavelength range from 0.4 to 14.4 μm in 36 spectral bands [1-3]. Both Terra and Aqua MODIS RSBs are known to be sensitive to the polarization of incident light according to analysis of their prelaunch test data, particularly at short wavelengths [4-5]. These results indicate that the polarization sensitivity increases with the angle of the incidence (AOI) on the scan mirror and there is up to ±5% impact of the linearly polarized light. Furthermore, there is a significant difference in the polarization sensitivity between the two sides of the scan mirror. Although the Terra and Aqua MODIS polarization sensitivity was generally comparable at prelaunch, considerable evidence from on-orbit data shows that the sensitivity of Terra MODIS has significantly increased, while Aqua

MODIS has been relatively stable. Sensitivity to polarization mostly affects ocean color data products that rely heavily on the measured radiances in the visible bands [6]. The NASA Ocean Biology Processing Group (OBPG) developed a vicarious calibration method by reference to the polarization-insensitive Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) to characterize the Terra MODIS on-orbit polarization impact [7-8]. Studies by MODIS land team showed that the unaccounted polarization sensitivity in Terra MODIS produced noticeable artifacts in surface reflectance and aerosol optical thickness retrievals [9-10] In our early studies, an independent vicarious approach that relies on the reflectances obtained from the pseudo-invariant calibration sites in the north Africa desert was used to determine the polarization parameters for Terra MODIS [11].

MODIS RSB calibration is performed for each spectral band, detector, subframe and mirror side [12]. Because MODIS is a scanning radiometer, the response versus scan angle (RVS), initially derived from pre-launch tests, also needs to be constantly characterized for on-orbit changes. Prior to MODIS Collection-6 (C6), measurements at two separate scan angles for the SD and lunar view, with a linear approximation, were used to track the on-orbit RVS change. In C6, the measured top-of-atmosphere (TOA) response trends from pseudo-invariant desert sites obtained at multiple angles of incidence are used in combination with the SD and lunar data to track RVS changes [13]. However, the retrieved radiance from earth scenes is polarized depending on the atmosphere, surface type, wavelength, viewing and solar illumination angle. If MODIS is sensitive to the polarization of the at-sensor radiance, the quality of the gain and RVS derived after incorporating the TOA response trends obtained from the desert sites would be affected, particularly for a few Terra MODIS short wavelength bands. Our recent study indicates that the RVS derived using the desert response trends after correcting for the polarization effects shows a significant improvement in the long-term trending, reduced uncertainties in the forward prediction, and a more accurate per-pixel uncertainty calculation in the L1B product [11,14].

In this study, we examine the changes in the polarization sensitivity impacting the relative difference among all detectors within band. Results from prelaunch tests indicate that there is a noticeable detector dependent polarization sensitivity and it is expected such a dependency could change on orbit, particularly for Terra MODIS. Results from our approach that relies on reflectances obtained from the desert sites are not separated by detectors. An early study by OBPG showed that there is a very small detector dependence of the polarization coefficients based on data collected early in 2009[15]. Results of this study provide useful information on polarization impact and further improvement of the correction algorithm.

2. POLARIZATION CORRECTION

The TOA reflectance is normally polarized due to impact of a combined effect of the atmosphere and underlying surface. The degree of polarization of the reflected sunlight is further altered after the incoming signal passes through the optical components of polarization-sensitive sensors such as MODIS. The impact of the polarization-sensitive optical components of a given sensor to the incoming light can be described by the Mueller matrix, a 4 by 4 matrix that linearly transfers Stokes vectors from the input side of an optical system to the output side. Under MODIS viewing

geometry, the measured radiance by the detector after passing through its optical components is given by the first row of the Mueller matrix [16]

$$I_m = M_{11} I_t + M_{12} Q_t + M_{13} U_t \tag{1}$$

where I_m is the measured TOA radiance, I_t, Q_t and U_t are the Stokes parameters describing the linear polarization of the TOA at-sensor total radiance, I_t. Note that the TOA V_t component (circular polarization) of the Stokes vector is commonly assumed to be negligible with respect to the other components [7]. Equation (1) can be expressed as following after division by I_t

$$I_m/I_t = M_{11}(1.0 + m_{12}\, Q_t/I_t + m_{13}\, U_t/I_t) \tag{2}$$

where

$$m_{12} = M_{12}/M_{11} \tag{3}$$

$$m_{13} = M_{13}/M_{11} \tag{4}$$

The term M_{11} is the instrument gain adjustment, and m_{12} and m_{13} are polarization sensitive parameters.

The MODIS RSB calibration is performed for each band, detector, and mirror side [12,13]. The reflectance factor from the EV measurements is given by the following equation

$$\rho_{EV}\, cos(\Theta_{EV}) = m_1 d_{ES}^2 dn_{EV}(1 + k_{inst}\Delta T_{inst})/RVS \tag{5}$$

where m_1 is inversely proportional to gain at the SD AOI, d_{ES} is the normalized Earth-Sun distance (to 1AU), dn_{EV} is detector's response in digital number during the EV observation, k_{inst} is the linear coefficient to correct impact of instrument temperature variation from the reference temperature, ΔT_{inst}.

3. RESULTS

3.1. Polarization correction

Equation (2) is used to characterize MODIS polarization impacts. The term I_m / I_t is replaced with the reflectance normalized by the early-mission value. Ratios Q_t / I_t and U_t /It are determined from the 6SV (the Second Simulation of a Satellite Signal in the Solar Spectrum, Vector Radiative Transfer Code) model's simulations, given an input of the solar and viewing zenith and azimuth angles of MODIS overpasses, band spectral response functions, surface type and other data sets provided by default for atmospheric profiles of variables, such as water vapor, aerosol and ozone, etc [17-18].

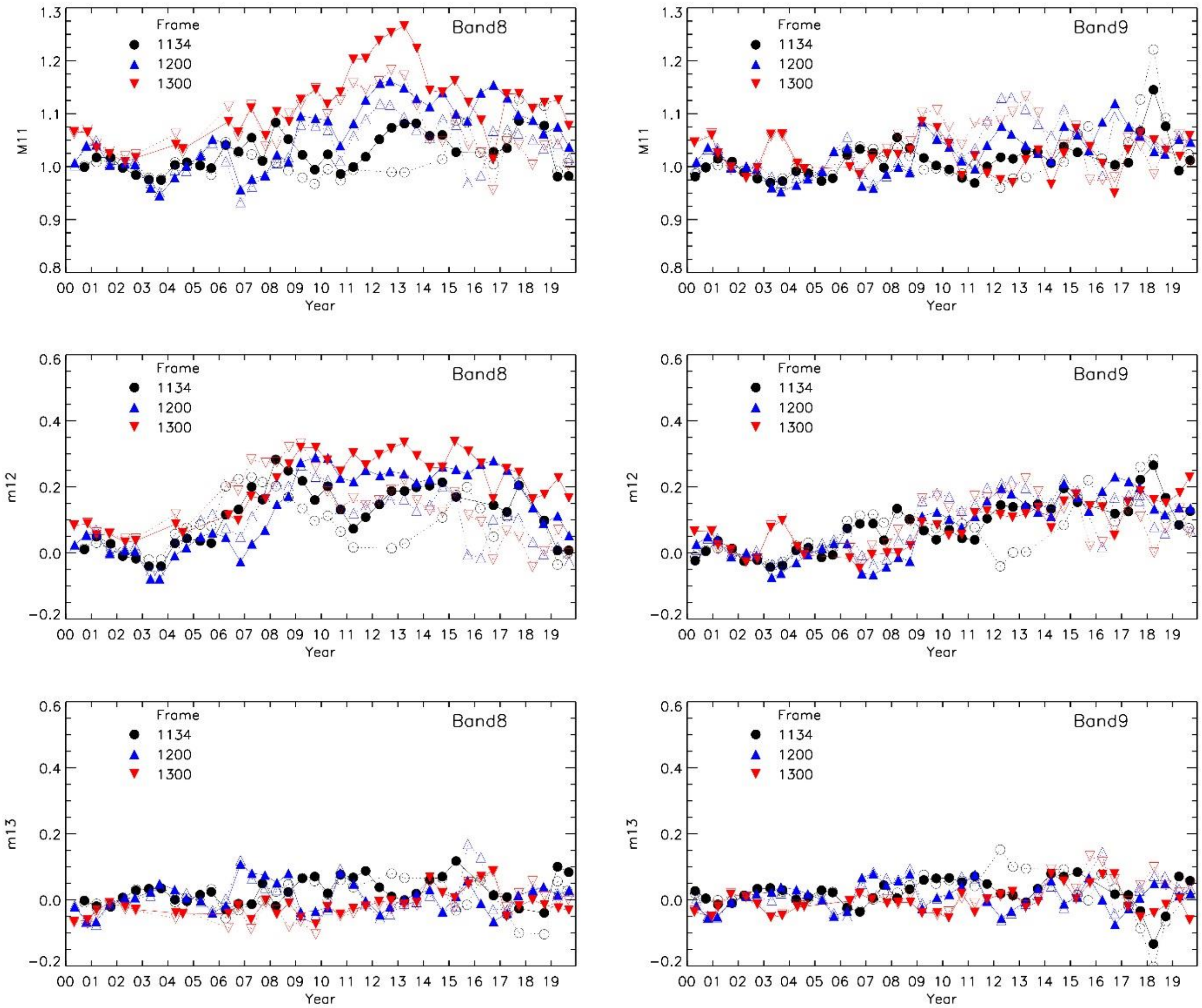


Figure 1. Trends of coefficients $M11$, m_{12} and m_{13} derived from the desert sites at three scan angles (frames 1134, 1200 and 1300) for Terra bands 8 and 9. Solid and open symbols are from mirror side 1 and 2, respectively. Site locations: Libya 4 (28.55°N, 23.39°E) for frame 1134, Egypt 1 (27.12°N, 26.10°E) for frame 1200, Sudan 1 (22.0°N, 28.5°E) for frame 1300.

For a given scan angle, the gain adjustment M_{11} and polarization parameters m_{12} and m_{13} are derived from a multivariable linear regression applied to equation (2). The reflectance data is collected from 16-day repeatable orbits, so the viewing angles for each desert site are nearly constant. This allows us to select various viewing angles over the entire scan angle range. To reduce the impact of data noise on the calculation of coefficients M_{11}, m_{12} and m_{13}, a one-year moving window is used for the regression. This significantly removes the impact of seasonal variations but also smooths out any rapid changes in instrument polarization sensitivity. Figure 1 shows the trends of M_{11}, m_{12} and m_{13} at three separate frames (scan angles) for bands 8 and 9. It should be noted that M_{11} is equivalent to an additional gain correction of the calibrated reflectance

provided by the Collection 6.1 L1B product. The trends of M_{11} show a strong scan angle and mirror side dependence for band 8 (0.41 µm), while for band 9 (0.44 µm), the magnitudes of variation are significantly reduced. The trends of m_{12} indicate that the polarization sensitivity is generally stable before 2007 (i.e., the initial six years). For band 8, it showed a rapid increase from 2006 to 2010 and stable behavior until recent years when it shows a decrease. A magnitude of m_{12} is seen to increase up to 35% for band 8. For band 9, however, the trends of polarization sensitivity were in upward direction after 2006. The results shown in Figure 1 are for three scan angles near the end of scan. Our results indicate that there is almost no change in the polarization sensitivity over the 1-800 frame range. For m_{13}, there is no significant increase through the entire Terra mission due to the nature of Rayleigh scattering, and therefore, m_{12} is a major contributor to polarization impact on MODIS. Results shown in Figure 1 are derived using reflectances obtained from the desert sites. Comparison with results from the OBPG, a cross calibration method applied in reference to a combination of the SeaWiFS and Aqua MODIS standard, shows a reasonably good agreement for M_{11} and m_{13}. In the case of m_{12}, results from the OBPG are slightly higher than those obtained from the desert sites (https://oceancolor.gsfc.nasa.gov/reprocessing/r2018/terra/).

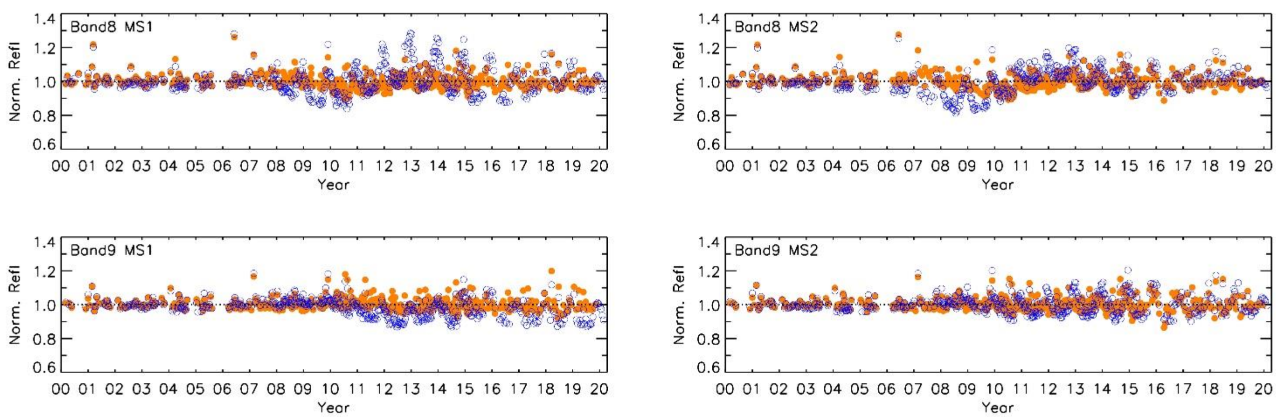


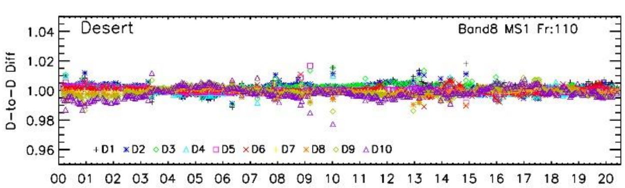
Figure 2. Trends of the BRDF corrected reflectances obtained from the desert site at frame 1300 before (blue open symbol) and after (yellow solid symbol) polarization correction for Terra bands 8 and 9. The left side of the panel is for mirror side 1 and the right side is for mirror side 2.

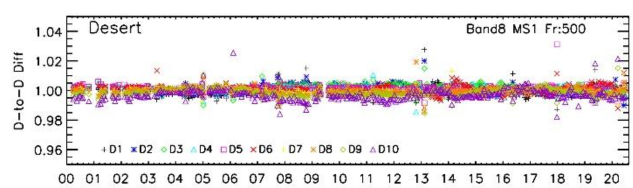
With derived coefficients M_{11}, m_{12} and m_{13}, polarization correction can be applied to the measured reflectance data by dividing the normalized reflectance trends by the right hand side of equation (2). Since the coefficients are band, mirror side, scan angle and time dependent, the polarization correction is also dependent on these variables. Figure 2 compares the reflectance trends at frame 1300 before and after the polarization correction for bands 8 and 9. Results are separated by mirror side. The polarization correction significantly reduces the magnitudes of the seasonal fluctuations. The fluctuation up to 35% before correction are reduced to within 10% after correction. It should

be also noted that there are noticeable residuals for band 8 after the polarization correction between 2010 and 2011. This is because there was a rapid increase in the polarization sensitivity during this period. Comparison between the results of the two mirror sides confirms that the polarization sensitivity is different between the two mirror sides. For band 8, mirror side 1 is more sensitive to polarization for most years after 2008. The polarization corrected trends are with similar fluctuation between the two mirror sides. Results shown above are for Terra MODIS. In the case of Aqua MODIS, there are no noticeable changes in polarization sensitivity over the mission.

3.2. Detector to detector difference

Results shown in previous figures are depending on band, mirror side and scan angle. Since up to 35% variations in reflectance are observed due to the impact of the polarization sensitivity, it would be expected that the polarization sensitivity among 10 detectors of each 1.0 km-pixel band can be different. A simple but effective method to examine the detector relative polarization sensitivity is to use a normalization approach. This is implemented as ratios of the detector dependent reflectances to the band averaged reflectance. Figures 3 and 4 show trends of reflectance separated by detector at various scan angles for band 8 and 9, respectively. The trends show an increased spread of detector to detector differences, particularly at large scan angles near the end of scan. As expected, the differences are generally larger for band 8 than those for band 9. Also as discussed previously, a rapid change in the detector to detector difference around 2010 for band 8 at frames 1200 and 1300 is coincident with the rapid increase in polarization sensitivity around the period. It should be pointed out that some of detector to detector spread may be due to a residual calibration bias among detectors [19]. Examination of the calibration coefficients derived from the SD also indicates a detector to detector bias. A reasonable assumption for the observed bias is due to the fact that each detector has a view from a slightly different area on the SD surface. As the SD continues to degrade, these areas may not degrade uniformly. Correction factors to account for the residual detector bias are derived from ocean surfaces and used in the MODIS calibration algorithm for selected RSB bands [15]. The noticeable seasonal fluctuations particularly at frame 1300 are due to a difference in polarization sensitivity among detectors. This is because each of the ten detectors with band has a slightly different optical path, causing differences in polarization sensitivity. Further examination of the results indicate that the largest difference occurs between detectors one and ten, since the ten detectors are arranged as a sequential line array.





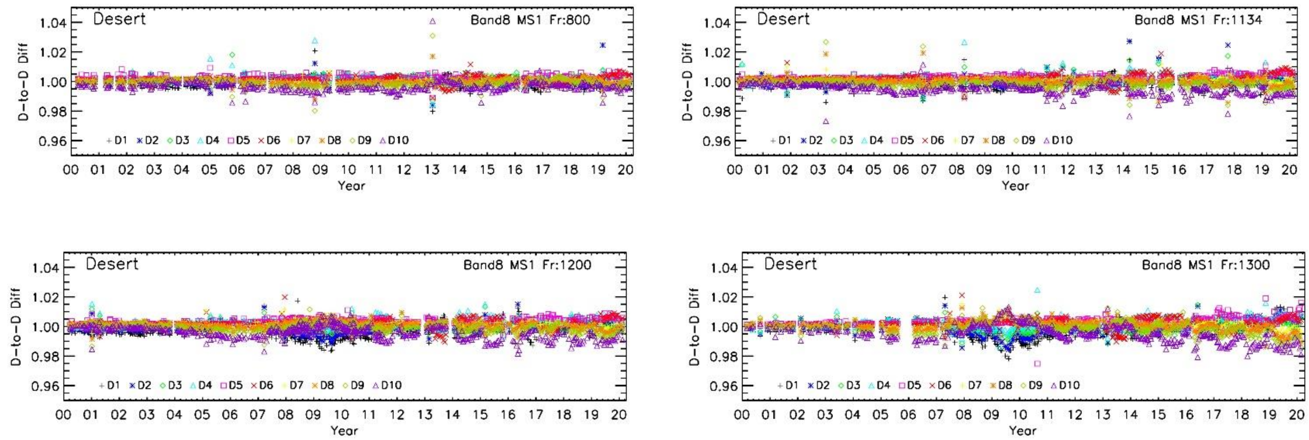


Figure 3. Trends of reflectance of each detector normalized by band average from the desert site at four scan angles (frames 110, 500, 800, 1134, 1200 and 1300) for Terra band 8 (mirror side 1). Site location: Libya 4 (28.55°N, 23.39°E) for frames 110 and 500, Sudan 1 (22.0°N, 28.5°E) for frame 800.

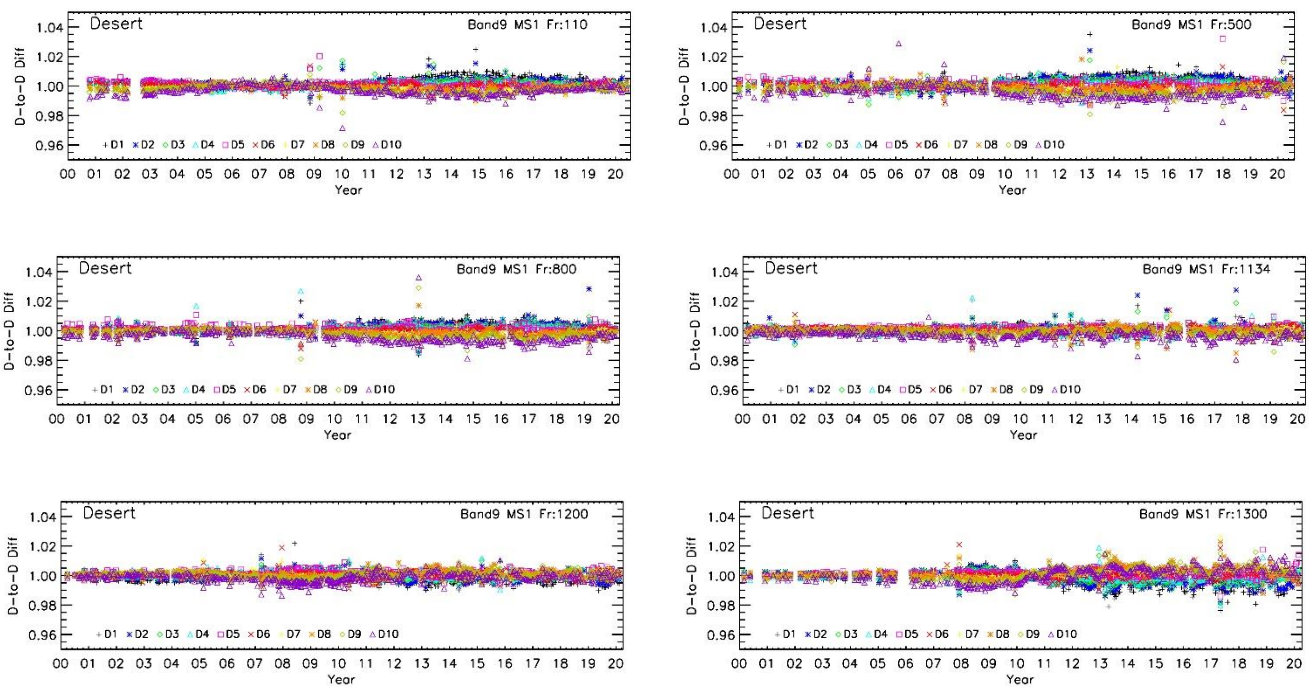


Figure 4. Trends of reflectance of each detector normalized by band average from the desert site at four scan angles (frames 110, 500, 800, 1134, 1200 and 1300) for Terra band 9 (mirror side 1).

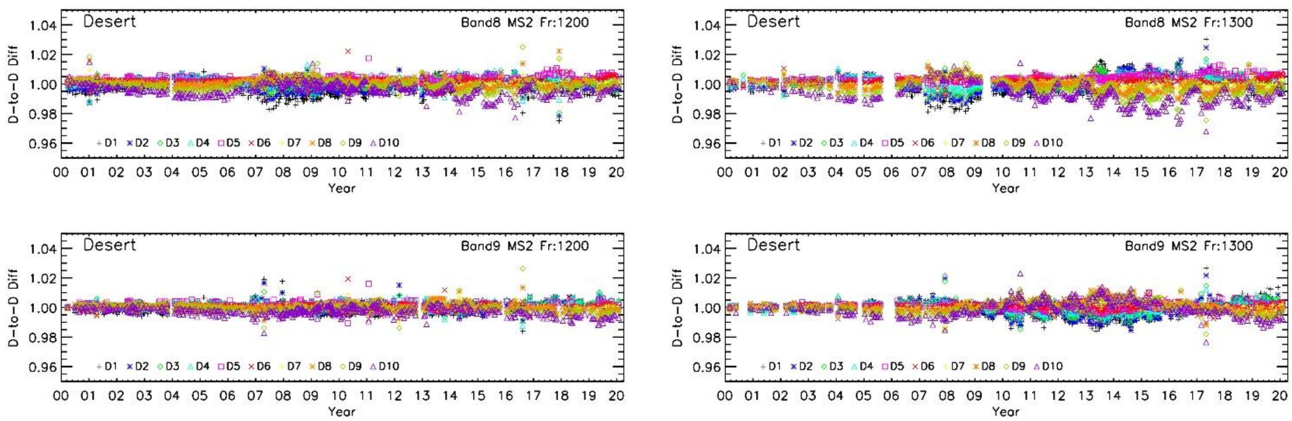


Figure 5. Trends of reflectance of each detector normalized by band average from the desert site at two scan angles (frames 1200 and 1300) for Terra bands 8 and 9 (mirror side 2).

Comparison with results from mirror side 2 shown Figure 5 indicates that the detector to detector spread and their magnitudes in seasonal fluctuation are slightly different depending band and scan angle. In terms of magnitude caused by polarization impact, an up to 1-2% fluctuation between detectors are observed near the end of scan. It should be noted that polarization correction algorithms as described here is applied to band, mirror side and scan angle. Results of this study indicate that a detector dependent correction only has a small impact on coefficients M_{11}, m_{12} and m_{13} and would help to reduce image striping near the end of scan.

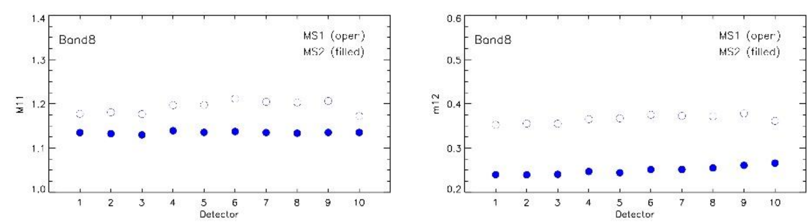


Figure 6. Example of coefficients M_{11} and m_{12} as a function of detector for band 8 (frame 1300) based data on April 3, 2015.

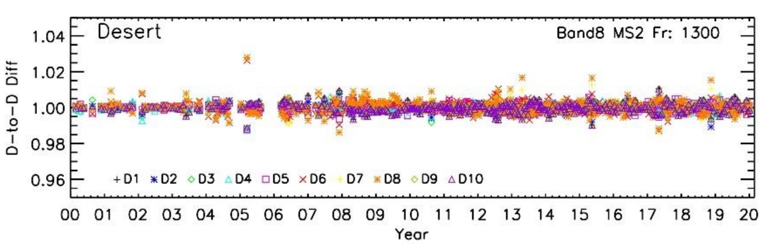


Figure 7. Trends of detector-dependent reflectance corrected by polarization for band 8 from the desert site (frame 1300, mirror side 2).

Figure 6 illustrates an example of detector-dependent coefficients M11, m12 for band 8 at frame 1300 based on results on April 3, 2015, when the instrument's polarization sensitivity was near its peak. As expected, variations in detector dependent polarization is much smaller than those due to wavelength, scan angle and mirror side. A detector dependent polarization correction (Figure 7) removes most of seasonal fluctuation compared with the uncorrected trend, as shown in Figure 5.

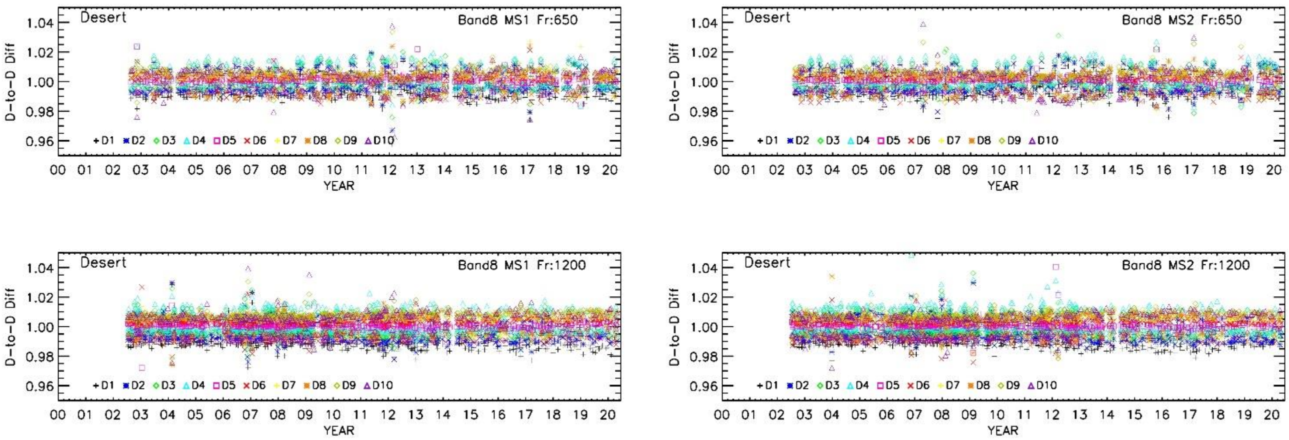


Figure 8. Trends of reflectance of each detector from the desert site normalized by band average at two scan angles (frames 650 and 1200) for Aqua band 8 (mirror sides 1 and 2). Site locations: Libya 2 (25.05°N, 20.48°E) for frames 650 and 1200.

In the case of Aqua MODIS, there is no noticeable change in on-orbit polarization sensitivity, although both Terra and Aqua MODIS polarization sensitivity were generally comparable at prelaunch. Trends of Aqua reflectance at various scan angles are have been relatively stable. Similar to the approach used for Terra MODIS, the same normalization method is applied to examine its detector to detector differences. Figure 8 provides trends of reflectance separated by detector at near nadir (frame 650) and end of scan (frame 1200) for band 8. The trends are highly stable and there are no noticeable seasonal fluctuations, although spread of detector to detector differences is slightly larger than those for Terra band 8, which is due to impact of site surface uniformity and existing calibration offsets among detectors. These results are consistent with those found in earlier studies that there is no significant change in on-orbit polarization sensitivity for Aqua RSBs.

4. SUMMARY

MODIS relies on a two-sided mirror that scans the Earth surface over an angular range from -55° to +55° off nadir. Its sensitivity to polarization was fully characterized in prelaunch conditions for each RSB, detector and mirror side as a function of scan angle. It was observed that while on-orbit polarization sensitivity for Aqua has been stable over the course of mission, the Terra polarization sensitivity for a few shortest wavelength bands showed a significant increase near the end of scan

angle after a few years in the mission. As a result, there are more than 25% changes in gain and 30% seasonal fluctuations observed in these bands. This study further examines the polarization sensitivity among 10 detectors of a few select shortest wavelength bands for both Terra and Aqua. A simple but effective way to examine the detector relative polarization sensitivity is to use a normalization approach, which is calculated as ratios of the detector dependent reflectances to the band reflectance. For Terra, results show an increased spread of detector to detector differences up to 1 - 2%, particularly at large scan angles near the end of scan. A detector-dependent polarization correction is able to remove most of seasonal fluctuations in detector to detector differences, which suggests that a detector dependent correction would help to reduce image striping near the end of scan. In the case of Aqua MODIS, as expected, there is no noticeable change in on-orbit detector to detector differences.

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